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RECORDING DOSIMETERS FOR ONE MICROSECOND X-RAY PULSES

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ABSTRACT

The use of Westinghouse "micro-flash" X-ray equipment for routine investigations has shown the need of a device for measuring the relative integrated intensity of each X-ray pulse. To satisfy this need we have developed two types of ionization chambers whose voltage outputs are proportional to the integrated intensity of a single X-ray pulse, provided the spectral distribution of the X-rays remains reasonably constant. The electronic circuits required to operate a recording meter are described.

(AEC abstract)

THEORY AND DESIGN OF THE IONIZATION CHAMBERS

The chambers were designed primarily to serve as monitors of the integrated intensity of the X-ray pulses produced by the Westinghouse micro-flash equipment.

The X-ray pulses are about one-half to two microseconds long and consist almost entirely of the continuous radiation from the tungsten target in the X-ray tube. The X-ray tube usually is operated at a peak voltage of about 300 to 360 kv and the effective wavelength is assumed to be about 50 X.U. This effective wavelength, however, depends somewhat upon the nature and amount of absorbing material in the beam. The use of an absorber of high atomic number such as lead causes a shift of the effective wavelength toward a smaller value whereas the use of a lighter element such as aluminum has less effect.

Since the detecting equipment consisted of small pulsed platinum-wall counters described elsewhere,[1,2] it was necessary to design an ionization chamber having approximately the same frequency response as that of the pulsed counters. According to Roberts et al,[3] the efficiency of a counter having a Pt wall is nearly independent of wavelength in the region near 50 X.U. From these considerations it was evident that the response of the ionization chamber should be nearly independent of the wavelength in the region from 100 to 50 X.U.

CYLINDRICAL IONIZATION CHAMBER

The details of the first ionization chamber installed are shown in Figure 1. The electrode assembly consisted of a brass cylinder three inches in diameter mounted on the end plate by three porcelain insulators. This cylinder served as the high voltage electrode. The collector electrode consisted of a steel rod also mounted on the end plate by means of a porcelain insulator. Electrical connections from the two electrodes were brought out through glass to metal seals.

A mixture of 90% argon and 10% carbon dioxide was used in the chamber at a total pressure of 100 lbs/in^2. These gases were purified by passing them over Ca metal pellets at 370°C for the argon and 250°C for the carbon dioxide.

The collector electrode was connected to a recording circuit which will be described in a later part of this report. A small time constant was introduced into this circuit in order to permit only the electron pulse to be recorded. The ionization chamber and recording circuit were mounted on the ceiling

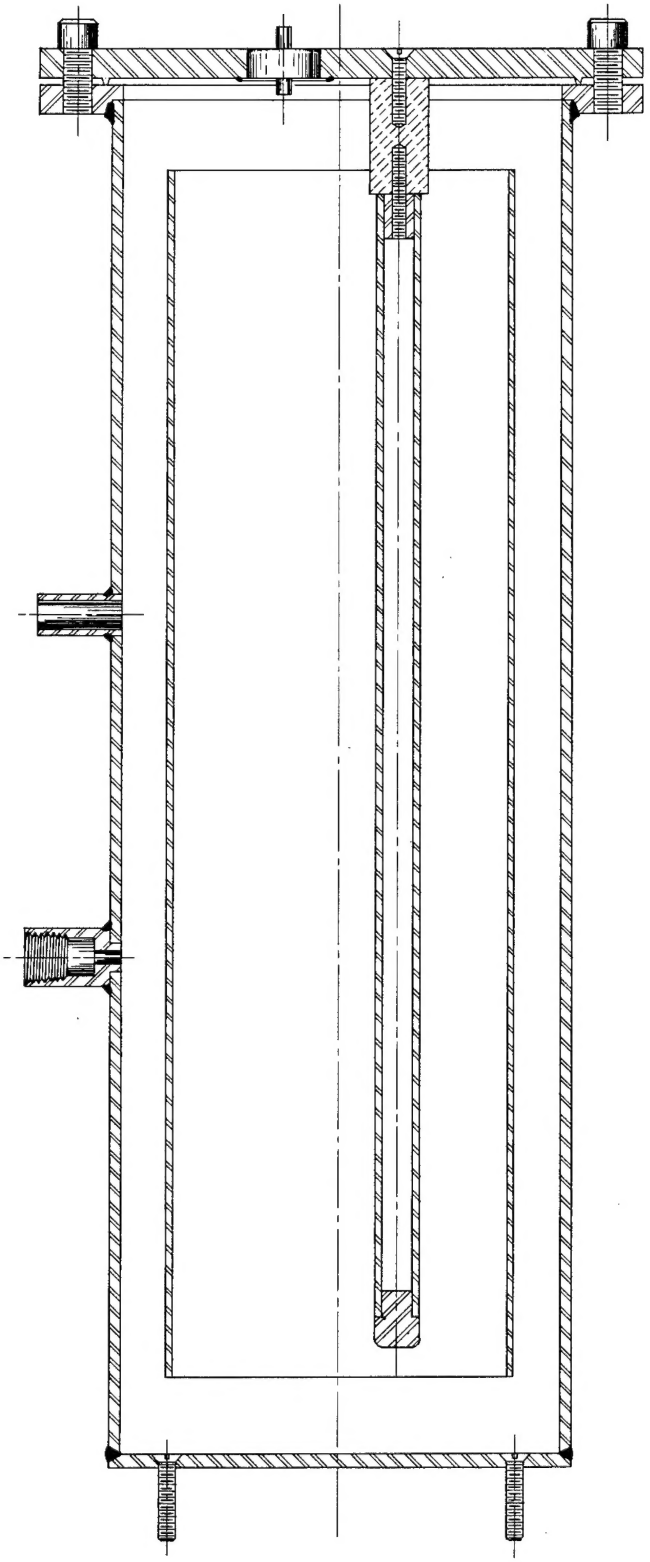

Figure 1. Sectional assembly.

of the X-ray building with the chamber at a distance of about ten feet from the target of the X-ray tube. Radiation leaving the target at an angle of about ten degrees with the surface was able to reach the chamber. No absorbing material other than the glass wall of the X-ray tube and the brass wall of the chamber was in the X-ray beam.

It is difficult to calculate the spectral response of this type of chamber because of the relatively large wall effects and the end effects due to the absence of guard rings. We can, however, estimate the approximate response. The overall response to X-rays of 50 X.U. is due to the ionization produced by electrons ejected from the walls and to the ionization due to the absorption of the X-ray beam in the gas. Since these two effects are of about equal magnitudes, we shall estimate the contribution from each of these effects to the total charge reaching the collecting electrode.

In calculating the relative numbers of electrons ejected from the walls and from the gas in the chamber we shall assume that the X-ray beam makes an angle of 45 degrees with the collector rod and is not limited by diaphrams. This is approximately the arrangement used. Since most of the electrons come from the inner surface of the cylindrical high-voltage electrode we shall consider only this contribution.

The number of electrons ejected per unit area from the inner surface of the high-voltage electrode by the absorption of a single X-ray photon in the metal is given by

$$n = (\mu/\rho)\ rf$$

where μ/ρ is the mass absorption coefficient corresponding to the assumed wavelength of 50 X.U. and r is an average range in gm/cm^2 of the electrons in the metal. For Cu at this wavelength μ/ρ is about 0.13, of which about 20% represents photoelectric absorption and the remaining absorption is due to scattering. The letter f represents a factor, which expresses the fact that the effective range of the electrons is less than r for the following reasons: the ejection of electrons at angles other than zero with respect to the X-ray beam, the straggling of the electrons as they are slowed down, and the variation of the energy of the recoil electrons with the angle of recoil in the case of absorption due to scattering. The average value of f for the two electrode surfaces is usually taken to be about 0.3. The maximum energy of the recoil electrons at zero angles with respect to the X-ray beam is about 60 kv, and the corresponding range of these is about 6×10^{-3} gm/cm^2. The yield of recoil electrons from the metal is

$$n_r = 2 \times .8 \times .13 \times 6 \times 10^{-3} \times .3 = 3.7 \times 10^{-4} \text{ electrons/photon}$$

where the factor 2 is introduced to take care of the fact that the X-rays pass twice through the high-voltage electrode.

The yield of photoelectrons from the walls can be estimated by assuming the average energy of the electrons to be 200 kv and using 20% of the absorption coefficient of 0.13 and f = 0.3. We have then

$$n_{ph} = 10^{-3} \text{ electrons/photon}$$

In order to estimate the number of electrons produced by the absorption in the gas in the chamber we calculate the absorption over a length corresponding to the passage of the X-ray beam at an angle of 45 degrees with respect to the collecting electrode. About two per cent of the original intensity is absorbed in this length. This absorption is almost entirely due to scattering. Thus:

$$n_{gas} = 2 \times 10^{-2} \text{ electrons/photon}$$

Apparently in this type of chamber the ionization is due mainly to the absorption in the gas.

We may estimate the variation of n_{gas} with wavelength by using an expression given in "X-Rays in Theory and Experiment" by Compton and Allison (p. 260) for the coefficient of absorption due to the energy spent in setting in motion the recoil electrons associated with the scattered X-rays. This absorption coefficient is given by:

$$\sigma_a = \sigma_o\ \alpha/(1+2\alpha)^2$$

where $\alpha = h\nu/mc^2$ and σ_0 is the classical value of the scattering coefficient. This expression may be modified to give the number of ion pairs produced in the gas if all the energy of the recoils is converted into ions. We have then:

$$n_{gas} \sim \alpha 2/(1+2\alpha)^2$$

This expression increases rather rapidly with decreasing λ for $\lambda < 50$ X.U. and less rapidly for $\lambda > 50$ X.U.

This type of spectral response is not much different from that of the Pt-wall counters mentioned earlier in this report. However, when the ion chamber was used as a monitor for the beam falling upon the counters, there was little if any correlation between the percentage firing of the counters and the output of the chamber. During this comparison there was no absorbing material between the X-ray tube and the chamber other than the walls of the chamber and X-ray tube, whereas a filter of 1/16 to 1/8 inch of lead was placed in front of the counters. The lack of correlation probably indicates that at times most of the energy in the X-ray pulse is shifted toward much longer wavelengths than the assumed value.

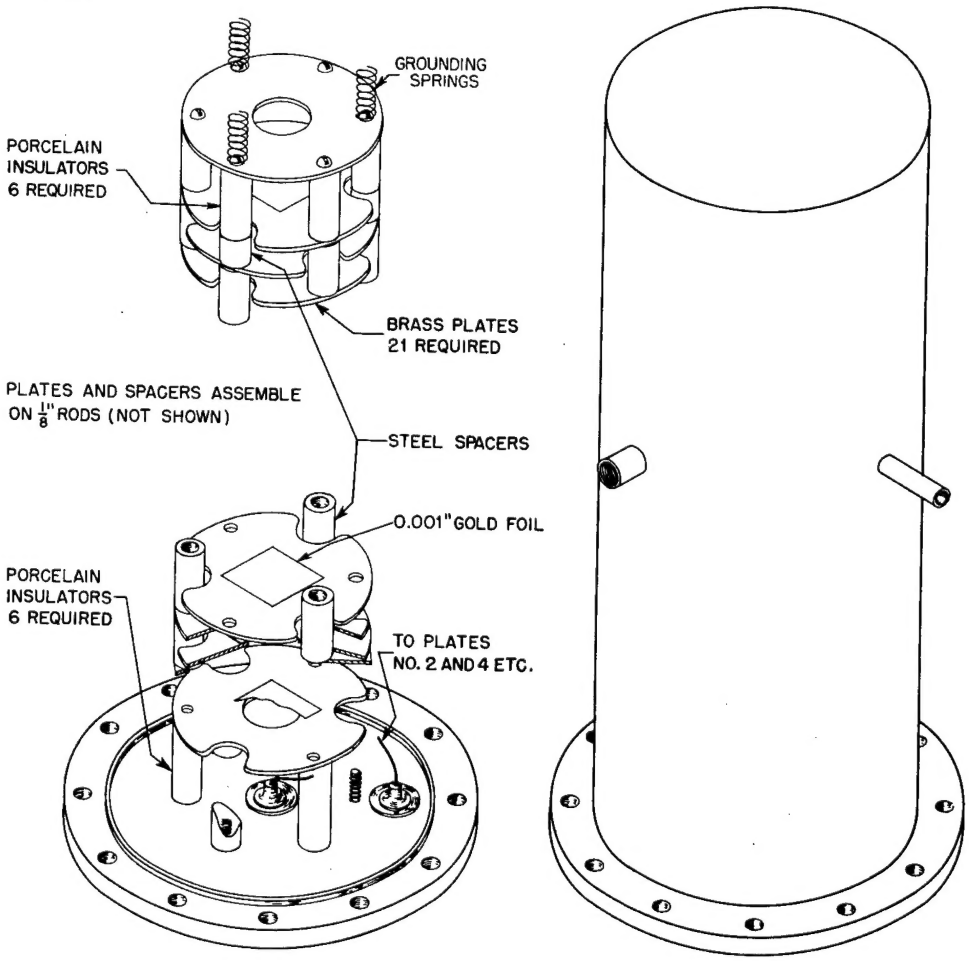

Figure 2. Parallel plate ionization chamber.

In order to have a monitor with a response similar to that of the counters, a chamber was designed in such a manner that most of the absorption occurred in the walls and very little in the gas. Alternatively, perhaps the chamber and its associated amplifier could be devised to have sufficient sensitivity to allow the same filter as used with the counters and to give the desired response. But because of difficult electric pick-up problems, it seemed best to proceed with the new chamber design. This chamber will be described in the following section.

GOLD FOIL IONIZATION CHAMBER

The details of the gold foil ionization chamber are shown in Figure 2. The electrode assembly consists of a series of 21 brass discs each having a 0.001-inch thick gold foil placed over a 3/4-inch diameter hole in the center of the disc. These discs are spaced at a distance of one cm by steel spacers supported on steel rods. Alternate discs are connected together, one set serving as the high voltage electrode and the other as the collector electrode. Each set is supported on three porcelain insulators at each end of the assembly. Electrical leads are brought out through metal to glass seals in the steel base plate. The electrode assembly is placed in the brass shell shown at the right in Figure 2. A pressure gauge is inserted in the threaded nipple and a needle valve is connected to the short tube.

A mixture of 90% argon and 10% carbon dioxide at a pressure of 50 lbs/in^2 is used. The high voltage electrode is connected to a voltage of 2000 positive with respect to ground. A preamplifier and amplifier of the type described later in this report are used to amplify the voltage produced by the charge on the collector electrode. The total voltage gain is 250 thousand. A time constant of 100 microseconds is introduced between the preamplifier and the main amplifier in order to amplify pulses due to electron and not positive ion collection. An integrating circuit of the type also described in this report is used to operate a recording milliammeter.

The yield of photoelectrons from the gold foils in the chamber is much greater than the yield of recoil electrons in the gas. Since the absorption in the gold varies with wavelength in almost exactly the same manner as the absorption in the platinum walls of the counters, this type of chamber should show the same spectral response as that of the counters if both devices responded equally to every electron ejected from the metal walls. We assume that every electron leaving the inner wall of a counter tube causes a discharge which is recorded as a count. However, the ionization produced in the gas between the gold foils in the chamber is a function of the energy of the electrons ejected from the foils. If we assume that the ionization is proportional to the average energy of the photoelectrons, the charge collected will increase with decreasing wavelength. This variation with wavelength is decreased somewhat in the present chamber since the stopping power of the gas between the plates is insufficient to stop the most energetic electrons. This will emphasize the contribution from the less energetic electrons produced when the wavelength is increased.

The following experiment was performed in order to establish the correlation between the readings of the gold foil dosimeter and the statistical operation of a number of platinum-wall pulsed counters one mm in diameter. Forty-three of these counters were placed at the detector post at a distance of about 20 feet from the X-ray tube. The ionization chamber was placed in front of the detector post and slightly to one side so as not to obscure the opening in the front of the post. The X-ray tube was operated at 280 kv. A filter of 1/16 inch Pb was placed in front of the tube, and therefore attenuated the beams to both the chamber and the counters. Both beams were further adjusted in intensity by Al filters until the appropriate counter response was realized. It was necessary in addition to reduce the intensity reaching the chamber by another Al filter, this one 5 1/2 inches thick. Simultaneous readings of the dosimeter and the number of counters fired were taken for each X-ray flash.

The data were tabulated in intensity intervals of one-tenth the maximum reading of the dosimeter. Figure 3 is a plot of the per cent firing of the 43 counters against the dosimeter reading. The solid curve is the exponential law which the counters are expected to follow. Apparently, there is good

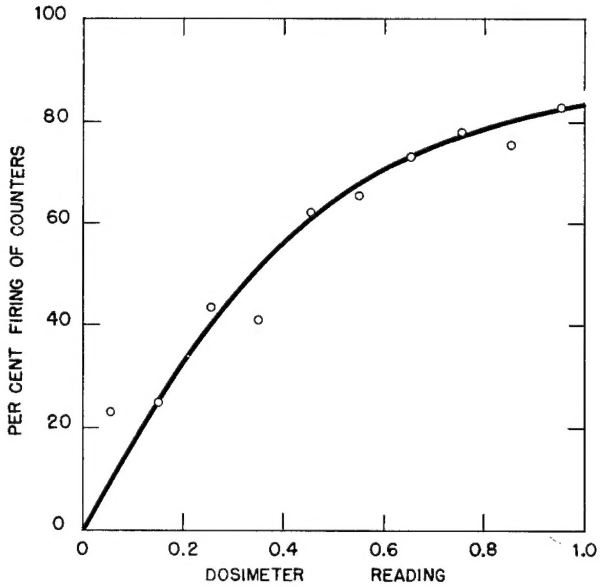

Figure 3. Per cent of firing of counters vs dosimeter reading.

correlation between the operation of the counters and that of the dosimeter. However, there were a few X-ray flashes characterized by wide variations between the counter and dosimeter behavior. Evidently, at times there were wide shifts in the effective wavelength of the X-rays which the dosimeter failed to follow correctly.

THE AMPLIFIER

Figure 4 shows the circuit of the amplifier and driver used with the cylindrical ionization chamber.

The conventional feed-back amplifier (Tubes T_1, T_2, and T_3) has a gain of 100 and has a rise of about 1.5 μsec. It has better linearity than the meters used to give the final dosimeter output. A 5-meg input resistor is used to give an input time constant of about 100 μsec.

The finite electron collection time and the 1.5 μsec amplifier rise time do not appreciably affect the observed pulse height. The electron collection occurs in a time less than 1 μsec. This time and the amplifier rise time are small compared to the 100 μsec input time constant and so have little effect on the output.

No gain control is shown in Figure 4. A control may be added, however, to fit individual needs.

The amplifier used with the gold foil ionization chamber is similar to that shown in Figure 4 with the addition of (1) another section in the main amplifier having a gain of 100 and (2) a preamplifier having a gain of 25.

THE DRIVER CIRCUIT

A novel feature of the electronic circuits is the driver circuit, Tubes T_4 to T_9 of Figure 4. The purpose of this circuit is to lengthen the short output pulse of the amplifier in such a manner that an ordinary meter may be used to record the pulse height. This purpose is accomplished essentially by charging a condenser to the maximum pulse voltage. Employment of a diode rectifier prevents the discharge of the condenser so that its voltage change may be permanently applied to the grid of the

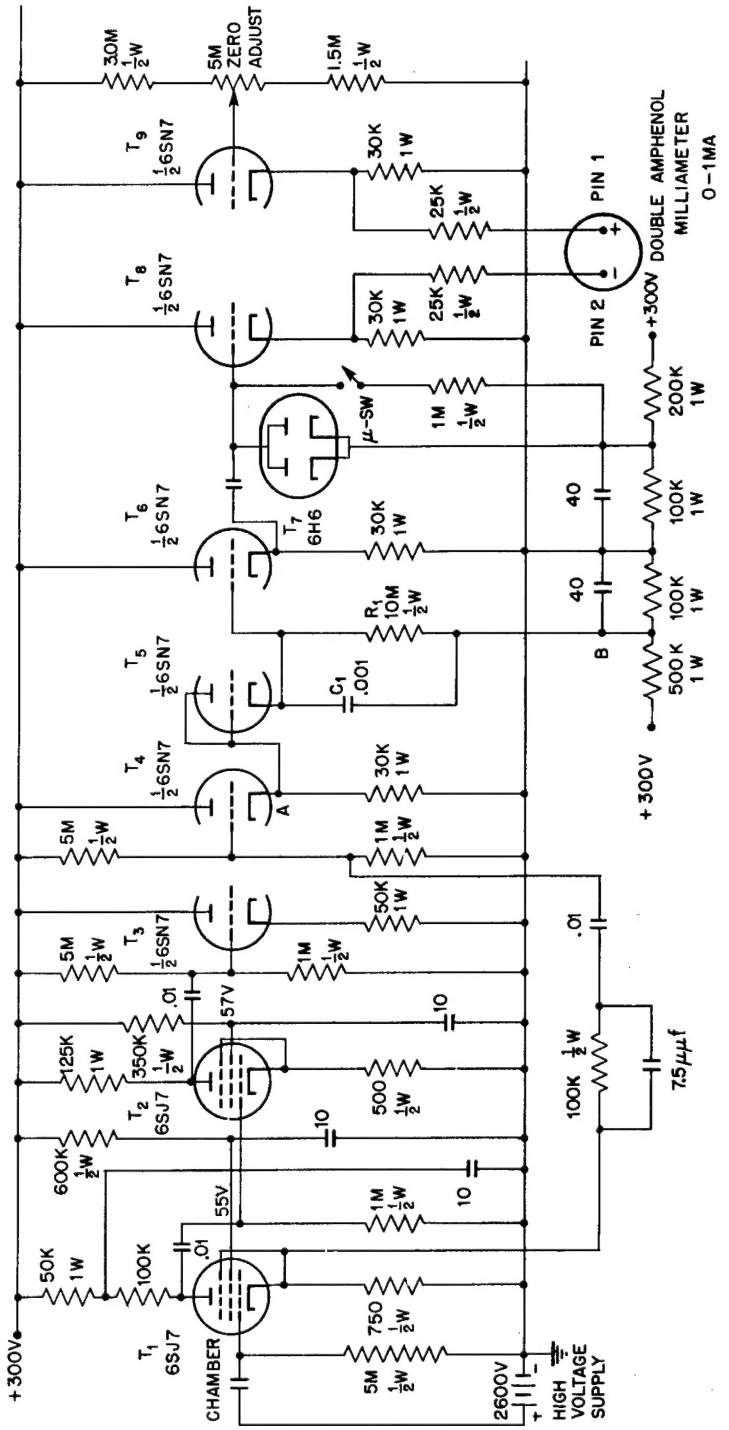

Figure 4. Dosimeter amplifier and driver.

cathode follower. This last tube is then used in a vacuum tube voltmeter circuit to drive a milliammeter to a constant reading.

In more detail, the action of the circuit occurs as follows (for simplicity we will for the present neglect the gains of the cathode followers): A fast pulse having a rise time of 1.5 μsec and a decay time of 100 μsec appears at the grid of T_4. This cathode follower is loaded by C_1 and R_1 through the diode T_5. It is required that C_1 charge up to the peak value of the pulse. For this to occur properly, the charging circuit must have a time constant small compared to the pulse decay time. The time constant is determined by the output impedance of T_4 (385 ohms) plus the diode resistance (500 ohms). The value is $(385 + 500)\ (0.001)10^{-6} = 0.9$ μsec. We find that this is small enough compared to the pulse decay time so that C_1 charges up to essentially the full signal voltage. After charging, C_1 discharges comparatively slowly with a time constant of 0.01 sec through R_1. The grid of T_6 follows this slow discharge.

The condenser C_2 loads the cathode of T_6 through the diode rectifier T_7. The grid of T_6 is held positive for a relatively long time by the time constant $R_1 C_1$ of 0.01 sec. Such a time enables T_6 to fully charge C_2 through its diode rectifier T_7. This process is completed before the voltage at the grid of T_6 has decayed appreciably, since the charging time constant turns out to be only 63 μsec by a calculation similar to the one above. In this calculation, we use 840 ohms for the plate resistance of the 6H6 to get $(840 + 500)\ (.05)10^{-6} = 63$ μsec. The grid of T_8 stays at ground potential during the charging of C_2 up to the maximum signal voltage.

Eventually the cathode of T_6 decays to its quiescent potential from the maximum pulse voltage. Since the charge on C_2 cannot leak off, the grid of T_8 follows this decay and is driven negative by an amount equal to the signal voltage. Under ideal conditions the grid would remain in this state indefinitely.

The cathode of T_9 is constant and adjusted to the quiescent potential of its twin in T_8. The cathode potential of T_8 drops by the pulse value and stays there. The resulting steady current through the milliammeter shows the signal voltage. The microswitch discharges C_2 to bring the meter reading back to zero. The fact that each cathode follower in the circuit has a gain slightly less than unity results simply in a proportional decrease of output.

In an actual unit there exists current leakage between the grid of T_8 and ground. The three factors involved are insulation resistance, grid current, and grid emission. The first is negligible under proper design. Grid current will cause C_2 to slowly increase its original charge so that the meter will drift up scale. Grid emission causes C_2 to discharge after charged up so that the meter drifts down scale after the deflection. Practically, one chooses T_8 so that these effects balance. The result is a slow down drift of the meter from its initial reading. Our units drop to 70% of the final reading in times of the order of 10 to 15 minutes.

The arrangement shown for the T_7 and C_2 was used to eliminate cathode-to-heater leakage. This leakage would parallel C_2 if used in the circuit of C_1 and T_5.

In some applications, potential of point B in the circuit should be adjusted to be 1 or 2 volts below that of point A. This optional refinement prevents the transmission of those negative signals which would affect the meter. As shown, the difference is near 8 volts and the unit will operate satisfactorily.

Two types of output meters have been used with the device. An ordinary dial 0-1 milliammeter is used when it can be read shortly after the deflection. An Esterline-Angus recording milliammeter is used when a permanent record is desired or when the meter cannot be read for some time after the deflection.

It should be noted that the calibration of the device depends on the resistance in series with the meter. If this is exactly 50 K as shown, the output sensitivity will be 1 ma for each 50 volts at the cathode of T_8.

THE POWER SUPPLIES

Figure 5 shows the power supply to operate the circuit of Figure 4. Because of the balanced output circuit of Figure 4, VR tube regulation is sufficient to keep a stable zero.

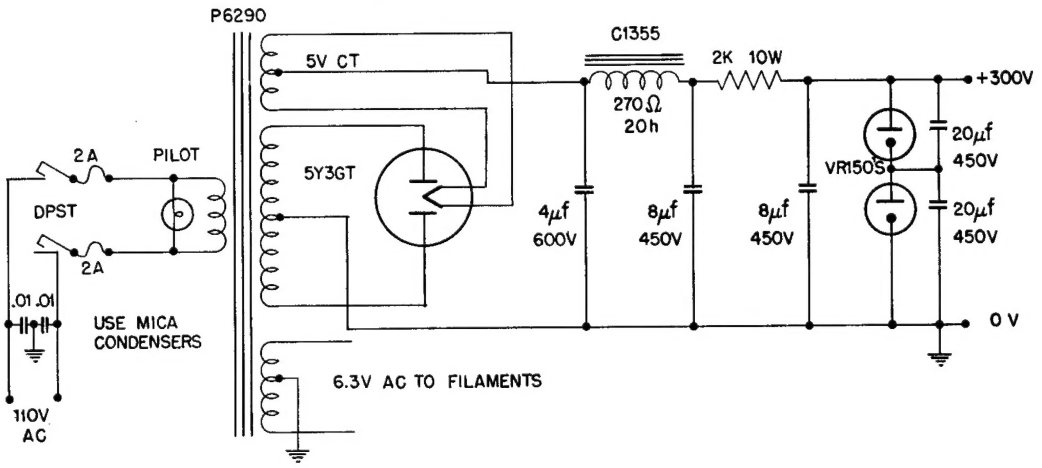

Figure 5. Dosimeter power supply.

Figure 6 shows the 2600 volt supply for the ion chamber. Since the output does not depend appreciably on the chamber voltage in this region, no regulation is required.

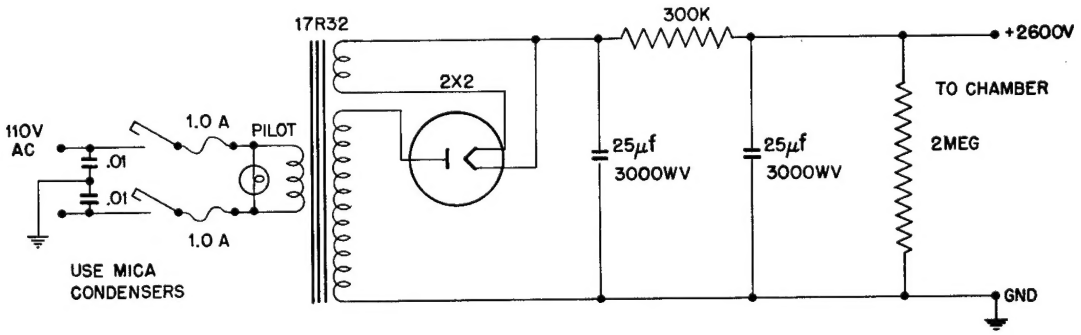

Figure 6. Chamber high voltage supply.

BEHAVIOR OF THE UNIT

Stability and Time Decay

The zero-drift of the unit is 0.01 ma over a period of an hour or so. This property varies from unit to unit. Slight gradual drifts are to be expected because of the open grid of T_8. With the μ-switch closed, drift is negligible. The balanced nature of T_8 and T_9 also tends to maintain the zero. After reaching maximum deflection, the meter gradually drops to 70% of its reading in the order of 10 to 15 minutes.

Linearity and Consistency

Figure 7 shows a graph of the overall linearity. A laboratory square pulse generator* furnished known input pulses at the grid of T_1. The output meter was a small 2% G.E. 0-1 milliammeter. The graph is plotted from the data of Table 1.

Table 1.†

Input pulse height (volts)	Output reading (ma)
0.0	0.0
0.2	0.38
0.3	0.61
0.4	0.82
0.5	1.04

† Each value is the average of 5 trials.

Table 2.

Trial (0.30 v input)	Output (ma)
1	0.610
2	0.605
3	0.610
4	0.615
5	0.615
6	0.605

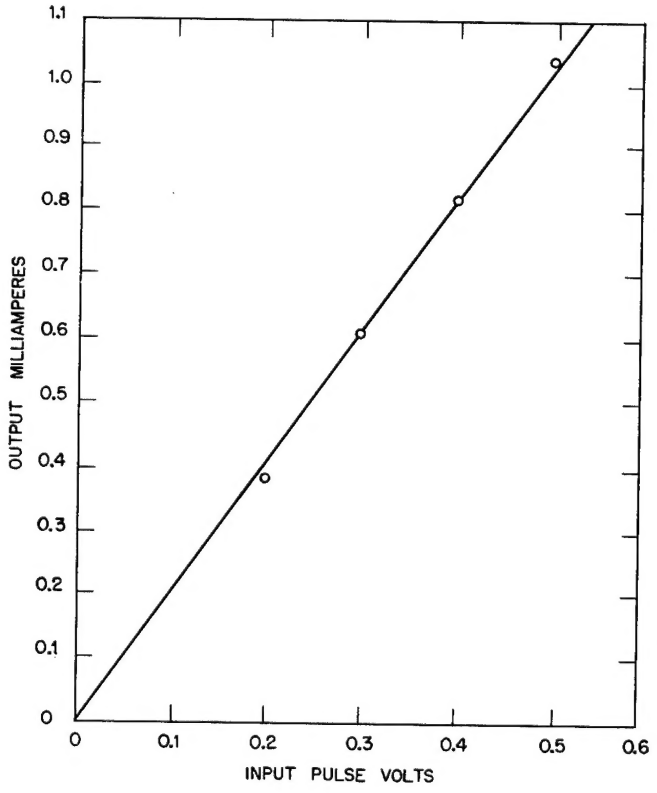

Figure 7. Dosimeter output vs input.

* This instrument gives pulses of uniform height and of value known to within 2%. The pulse rise time is about 1 μsec.

The consistency of the unit in its mid-range is shown in Table 2 which gives 6 pulses at a constant 0.30 v input. The average is 0.610 and the maximum deviation from this is 0.005 ma or less than 1%.

Gains

The overall sensitivity S of the circuit shown in Figure 4 is given by

$$S = (\text{ma output})/(\text{volts input})$$

$$S = 0.82/0.40 \text{ ma/v} = 2.05 \text{ ma/v}$$

The voltage gain to the cathode of T_8 can be found by assuming that 50 volts output give 1 ma;

$$\text{Gain} = S \times 50 \text{ volts/ma} = 102$$

The combined gain of cathode followers T_6 and T_8 was found to be 0.89 by oscilloscope. This gives a gain of 0.94 for each.

MECHANICAL ARRANGEMENTS

Several methods of arranging the dosimeter elements have been used. In the first models, the chamber was bolted to the amplifier chassis while the power supplies were contained in two separate chassis. More effective shielding was obtained in later models by putting all electronic gear on a single shielded chassis with the chamber bolted on as before.

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